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A REVIEW OF VARIABLE VALVE TIMING DEVICES

**A thesis submitted in partial fulfillment
of the requirements for the Honors Program, for the degree of
Bachelor of Science in Mechanical Engineering**

by

P. Blair Shelton, Mechanical Engineering

**Thesis Advisor – Dr. Larry Roe
Dr. Adam Huang**

**May 2008
University of Arkansas**

Acknowledgements

I would like to thank Dr. Roe and Huang for their continued support and guidance of my automotive research, Vanessa for bringing me food on those long nights of research, Aaron for helping with the formatting of this paper and my father for inspiring my love of cars.

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List of Abbreviations

bsCO- brake specific carbon monoxide; the measure of carbon monoxide emissions divided by engine output
bsfc- brake specific fuel consumption; the measure of fuel consumed divided by engine output
bsHC- brake specific hydrocarbon; the measure of hydrocarbon emissions divided by engine output
bsNO_x- brake specific nitrogen oxides (NO and NO₂); the measure of nitrogen oxide emissions divided by engine output
CO- carbon monoxide
CID- cubic inch displacement
DOHC- dual overhead cam; a set of cams for the intake and exhaust valves
ECU- electronic control unit
EGR- exhaust gas recirculation
EIVC- early intake valve closing
HC- hydrocarbon
I6- six inline cylinders
L- liter
lb- pound
LIVC- late intake valve closing
m/s- meters per second
mm- millimeter
ms- millisecond
NO_x- nitrogen oxide (NO and NO₂)
rpm- rotations per minute, normally of the crankshaft
V8 – eight cylinder engine
VVT- variable valve timing
W- watt

Abstract

Variable valve timing (VVT) has evolved from simple, manual controlled engine management to automatic, electronic works of engineering. Starting from the need for more power and extending into fuel efficiency and low emissions, VVT has evolved from the constant changing of needs. This paper summarizes various devices used to control the timing of valves from the early 1920s up until 2007.

Purpose

The purpose of this paper is to compile data from various sources regarding variable valve timing. In specific, the evolution of variable valve control systems from purely mechanical to electro-mechanical and even into almost total electrical systems. The outcome is to show that the valves will eventually be electrically controlled in full. Some factors that will be discussed in general include: emissions, fuel economy, feasibility and output. Through relevant papers written by others and through the writer's own observations, a viable prediction of future trends is anticipated to be met.

Definition

Internal Combustion engines need fuel and air to function. These are brought in through intake valves which open and close during the intake stroke of the piston. The valves used in the automotive field are generally poppet valves; they normally are flat and circular at the bottom end and taper upward, into a thin stem. The combustion process results in gases being formed and these leave through exhaust valves during the exhaust stroke. Cams control these valves and some cars use separate cams for intake and exhaust valve (dual overhead cams). Generally the exhaust valves remain open for up to a 20° crankshaft rotation during the intake stroke because the momentum of the outgoing exhaust gases help to bring in the intake charge and then the intake charge helps remove the remainder of the exhaust gas (Duleep et al., 2004). This is referred to as valve overlap and is very important in the scheme of variable valve timing. The timing is generally set to perform at a compromised setting for covering the entire rpm range. Advancing or retarding the opening and closing of valves can reap large improvements in torque, emissions and fuel consumption. A further explanation of this process is provided in the November issue of Car and Driver, written in 1991, which is attached in appendix B.

Ahmad and Theobald (1989) classified the different VVT systems into five different groups based on level of sophistication. While this paper sets out to categorize systems based on the level of electronics used, Ahmad's class system satisfactorily achieves the job of breaking them down into other groups based on the extent of timing variation.

1. Systems which have variable overlap periods.

2. Systems which have fixed lift and use two different settings for VVT.
3. Systems which have fixed lift but provide continuous phasing.
4. Systems which have fixed lift but can modify the lift profile continuously.
5. Systems which have variable lift, duration and phasing.

(Ahmad et al., 1989)

These groups evolve from one another as the technology and research comes available.

The list is a good reference to keep in mind as the various systems that follow are explained.

Early History

A patent was issued in 1899 that addressed the controlling of valves independently in engines (Gould et al., 1991). The author realized that controlling each valve independently would result in a wider power band. In late 1920, Automotive Industries published an article regarding a variable volume, variable valve timing engine. During the time, a barrel of oil had increased from \$10 in 1915 to \$27 in 1920 and fuel efficiency was the main issue. The engine could raise or lower the crankshaft to vary the compression ratio of the cylinder. This was achieved by the flow of oil to a hydraulic piston which was controlled by a pump driven by the crankshaft. Of importance to this paper is the ability of the cams on the camshaft to slide and change the closing points of the valves. The only time the intake valves were timed differently was through the compression stroke, therefore changing the compression pressure (Automotive Industries, 1920). The pressure could be changed from ninety lb to fifty eight lb from startup speed to 2000rpm, respectively. The reasoning for the valve timing variations according to Charles Salisbury, the inventor, is to increase the volumetric efficiency at lower engine speeds (11% to be specific). In actual tests of the engine equipped in a car, increases of 21% and 36% were seen in fuel economy at 8 and 22 miles per hour, respectively (Automotive Industries, 1920).

In 1933, a test rig was developed for aircraft engines that could vary the valve lift, opening and phase while the engine was being operated (Aircraft Engineering). The main objective was to increase output of the engine. This was one of the first engines to use dual cams for controlling the intake and the exhaust valves and was also had an overhead setup therefore being one of the first dual overhead cam engines (DOHC).

Although suited to be changed while running, all the controls were manually adjusted by hand. For the valve lift, a small cam A lifts a lever B, which then lifts up a slider that in turn lifts a rocker C and changes the valve lift amount. The slider is controlled by a handle that can be manually operated (Figure 1). This was a step in the direction of current VVT configurations, based on the fact that it could be used while the engine was running, but required a manual input that would eventually be replaced by an electronic control.

In the 1960s, pollution began to be a major issue and the main reasoning for research into VVT was to reduce hydrocarbon and carbon monoxide emissions. In a paper by Hagen et al. (1962), they showed that emissions were highest with lower engine speeds but that at high engine speeds, the increase in airflow can also attribute to an increase in pollutants (Figure 2,3). They also discussed the high amount of pollutants produced at idle and deceleration and experimented with the valve overlap. By decreasing overlap, it was reasoned that the fuel-air mixture would be of a higher quality and therefore the hydrocarbon concentration would be smaller. This hypothesis was only correct for a certain range of air-fuel ratios, but for the air-fuel operating range of the carburetor (10-12) the reduction in overlap actually increased the concentration of hydrocarbons (Hagen et al., 1962). Past a ratio of 15, the decreased overlap helps with the hydrocarbon problem, but was shown to make little difference in carbon monoxide concentrations. This was further shown in Freeman et al. (1972). The engine used in Hagen's paper had mechanical valve lifters that not only adjusted valve overlap, but also controlled each valves' amount of time open. This could have had an effect on the results and, therefore, these results should be taken skeptically. Freeman's paper focused

more on the elimination of nitrous oxides, something that the Hagen paper never mentioned. Using an apparatus that could vary the camshaft timing based on oil flow in the solenoid, the timing was retarded or advanced at conditions other than idle or wide open throttled (Figure 5). The controls were not fully automatic but the design was one that would eventually reach a level of automation.

Schiele et al. (1974) published a paper detailing the design of a camshaft that would change the timing of the intake valves relative to the exhaust valves. This design used a camshaft with movable pieces. The intake cams could slide on the axis of rotation and would rotate to change the timing (Figure 6). The exhaust valves would be unaffected due to the interior design of the cams (Schiele et al., 1974). In the engine setup, using a 350 CID V8, the new cam fit into the space left vacant by the stock one (Schiele et al., 1974). Each camshaft had five individual cams fit onto a driveshaft and was hydraulically operated. In the reliability test, the timing of the intake cam was continually changed between 0 and 40 degree advancement. The results of these schemes were documented (Figure 7). At higher rpms, as can be expected, the timing actually hurt the power and torque outputs. At lower rpms, the advances slightly improved torque and did not affect power. As far as emissions are concerned, these tests showed that NO_x quantities were greatly reduced but HC and CO were mostly unaffected. The high air fuel ratio (13:1) achieved during advanced intake timing attributed to a slight increase in the HC and CO emissions and was a main factor in decreasing NO_x concentrations.

Introduction of Electronic Controls

Beginning in the 1980s and leading up to the present, emissions and fuel economy have taken precedence over power output in the development of valve timing schemes.

To increase efficiencies, losses in the engine are being closely examined and reduced where possible. One of these losses occurs in throttling incoming intake air. At wide-open throttle, the incoming air faces very few obstacles and the internal combustion engine is most efficient at this point. Realistically, automotive engines spend a majority of their time at part-throttle. Elrod and Nelson looked at this and decided to use valve timing to throttle the engine. They used a design similar to Schiele's design: a camshaft with rotating cams for intake timing (Figure 8,9). To dynamically control the timing, a harmonic drive is used. This mechanical power transmission unit is powered by an electric motor and uses electronic controllers to read intake-timing sensors and change the hexagonal camshaft (Elrod et al., 1986). The advancing of intake timing at wide-open throttle decreases power and brake specific fuel consumption (bsfc), which is needed to "slow" down. Less power is produced and the vehicle's weight stays the same, so the vehicle will slow. The reasoning behind a reduction in bsfc is due to the fact that as less power is produced, a larger percentage is needed to overcome frictional effects and essentially reduces the efficiency of the engine (Elrod et al., 1986). No final results were given for the fuel efficiency. Based on the supplied information, however, it can be assumed that fuel efficiency will be increased. The engine produces power when the load required it.

Another paper, written by Lenz et al. (1988) approached the same issue, but described multiple systems and discussed their feasibility in controlling the throttle. The hydraulic approach used either a slide or solenoid valve to control oil flow, which then proceeded to allow the intake valve to close early when needed. No mention of the control system for the slide/solenoid valve was mentioned. The mechanical system

analyzed used a series of cams to control the closing of the valve (Figure 10). The valve was opened by a rocker arm C, which was controlled by the cam A. If the valve needed to be closed early, the control cam B could simply be turned so that the small radius side of B was touching the rocker arm (Lenz et al., 1988).

In 1982, Alfa Romeo introduced a hydro-mechanical system in cars to help with starting and idling issues encountered while dealing with United States emission standards. The system was very basic and only had two different settings. One setting was the standard cam format for a compromised vehicle and the other setting advanced the inlet cam by 10° at 1500 rpm (Scott, 1984). It used a helical gear and hydraulic piston with oil as the fluid to change the timing. In 1984, Alfa teamed up with Bosch to form a computer controlled intake timing system for use in Europe. For the newer version, the timing advances up to 16° based on the power needed (Scott, 1984). For a high rpm, light load, the system will remain neutral. When the load reaches a point at which the throttling cannot provide the engine with sufficient power, the timing is advanced. The benefit of coupling the timing mechanism with the Bosch computer is that the fuel injection and ignition timing can be controlled as well, to produce higher gains in economy, performance and emissions (Scott, 1984). Based on the comments in the literature, this was one of the first instances of a coupled system of mechanical and electrical components. Gray's 1989 review of VVT technology supported this by mentioning only the Bosch electro-hydraulic timing system and no others.

Electronic Control Units Come into Mainstream Use

Toyota incorporated an electro-hydraulic system into their 3.0L I6 engine in 1996 (Moriya et al., 1996). A pulley was used to control the speed of the camshaft relative to

the crankshaft, which was regulated by an oil control valve, which received its commands from the electronic control unit (ECU) (Figure 11). The ECU received inputs from the engine condition signaler, and the crank and cam position sensors. Comparing these inputs against a target cam angle allowed the ECU to determine whether the system needed to be held at current conditions, advanced or retarded (Figure 12). The system was constantly trying to match a particular current and did this with relatively small amounts of delay (Moriya et al., 1996). The system would reduce the overlap by retarding the intake closing as much as possible during idle and as the load increased, the intake would be advanced to increase the fuel efficiency and emissions (Moriya, 4). Torque was increased 10% due to the continuously variable timing scheme (Moriya, 6). Fuel efficiency increased 6%, where NO_x and HC output both dropped by 40 and 10%, respectively (Moriya et al., 1996). This setup showed the benefits of using an ECU to control variable valve timing, especially since it could control the continuous changing of the timing. The level of control was impressive for a system at this time.

An article in 2005 showed that the same type of system was still in use as before (Botti, 2005). It is a continuous unit with an oil pump controlled by the ECU. The engine's ECU controls the oil solenoid valve, which can direct flow to a rotor's two chambers to either advance or retard the timing of the camshafts. This technology is applied to the intake, the exhaust or both valves and shows improvements of 1-4%, based on the power trade-off (Botti, 2005). Another technology developed extensively by Delphi is two-step valve lift phasing. At part load, the intake valve is lifted from 3 to 7mm and at full throttle it is opened to 10mm. Fuel improvements over 5% have been shown and the engine's torque curve has been almost fully balanced (Botti, 2005). The

usage of variable timing and lift, through the use of cam controllers, has had extensive research money dedicated to it and is currently in use with most of the major automotive manufacturers. Something else being researched currently is the use of camless internal combustion engines.

Camless Internal Combustion Engines

In 1899, a design submitted for variable valve timing mentioned the use of a camless valve timing setup (Gould et al., 1991). Within this approach, there are a few solutions currently being developed. These include, but are not limited to: solenoids, electromagnets (electromechanical), electrohydraulic and electro-pneumatic. While all these systems pose great results for improvement of current internal combustion engines, they all suffer from various control issues. The velocity at which the valve approaches the seat is too high (seating speed), the amount of time it takes the valve to open is too long and the high power usage are a few of numerous other problems.

Pischinger and Kreuter proposed one of the first camless designs using two energized coils to attract a plate which is connected to the valve stem (Ahmad et al., 1989). Using this system, Kreuter recorded net specific fuel consumption increases from 0% (high load) to 40% at low load. He also recorded that the idle speed of the engine could be reduced from 800rpm to 500rpm (Ahmad et al., 1989). No specifics were listed for emissions, but he did mention an improvement in NO_x emissions using LIVC and improvements in HC with the EIVC. When Ahmad wrote his review in 1989, this was the only electromagnetic system mentioned.

Gould et al. worked extensively in 1991 on evaluating a camless engine setup using electro-pneumatic valve actuators and a programmable computer. Their test

involved comparing this engine with a similar one that used a conventional cam for valve timing. The actuators used pressurized air that was controlled by electromagnetic valves. The design met many of the current camless valve timing problems head on. Their comprehensive list of objectives helped to achieve this. Among these were variable lift, reliability, precise control and low cost (Gould et al., 1991). By using air, the response time was between 1.25 and 3ms and further testing yielded results compatible with engine rpms around 7200. The design is shown in Figure 13. Air is released through the electromagnetic latch and through the air valve causing the power piston to move. This piston, in turn, shuts off the high pressure air and allows the air to equalize. To address the problem of hard seating the valve, a small amount of air is left on the opposing side of the power piston. Once this air is compressed to a certain pressure, it is released to eliminate any “bouncing” of the valve. The pressure can be adjusted to control the valve more precisely. The system used was practical in all respects except for the high energy consumption. Where the current engine uses around 140W at 1500rpm, Gould’s system used around 2.5kW (Gould et al., 1991). Their results were promising despite the shortcomings of the system (Figure 14, 15). Late intake valve closing resulted in the lowest bsfc, which is counterintuitive due to the fact that closing the valve late results in higher amounts of work. This was explained by Gould as being mainly a result of the mixing of the intake charge. Normally this would occur due to the “slow” moving of the valve, but due to the short duration of valve movement in the new system, nothing substantial could be determined (Gould et al., 1991). Overall results were as follows: increases in maximum torque around 11%, 4.4% reduction in bsfc, and 60% reduction in

bsNO_x. Compared to a typical engine with EGR, the proposed design saw 15%, 4%, 9% and 5% reductions in bsNO_x, bsfc, bsHC and bsCO, respectively (Gould et al., 1991).

Marcello Montanari et al. did some work in 2003 to help with the control of an electromagnetic camless system. Although not a favorite of some previous reviews, it can be reasoned that this was due to a lack of research for most of the papers during their time. Using two electromagnets to control the valve eliminates the need for a cam, but presents some control issues. The biggest control issue has been the seating speed. Simply switching the magnets on and off yields issues since the current cannot be totally removed from either instantaneously. If things were ideal, the valve would approach each seat with zero speed. Montanari et al.(2003) proposed a variable voltage system to brake the valve on both approach and departure from closed. They cited high power usage as one of the primary problems. The high power usage is not limited to this system, as Braune et al. (2006) listed it and controls as issues with the current electromagnetic systems.

Another system designed in 2002 took the valve train into a whole new area. It had no torsion bar, but was controlled purely by electromagnets. This system, designed by Chun Tai et al. (2002) used two opposing electromagnets, two springs and the valve. The two springs keep the valve in a middle position when the magnets are not in use. The closing time of this system was reported at 2.76 seconds on average, with a seating velocity of 0.093 m/s (Tai et al., 2002). Although the closing time meets the requirements, the seating velocity still needs improvement to meet a standard of 0.05 m/s (Stewart et al., 2007).

Whereas previous papers focused on the seating speed as a problem of electromagnetic valves, Park et al. (2003) focused instead on the actual physical constraints on the design of a system. The valve in his design is controlled by the movement between two magnetic cores (Figure 16) much like most valve timing mechanisms of its kind. The magnetic cores are E-shaped with a coil wrapped within (Figure 17). For the hardware, Park was able to determine the mass of the armature, springs, valve and stems. Two crucial issues in his design report were the valve pitch and the height of the head cover (Park et al., 2003). Since the magnetic force is based on the size of the magnet, a rectangular parallelepiped was determined to produce the most volume (Park et al., 2003). This helped with fitting the entire package within the limits of the head covers and subsequently the hood of the automobile.

A large step forward was taken in the field of electromagnetic valve timing in 2006, when an article was published documenting the control of electromagnetic valve actuators within established standards (Stewart et al.). Using a system similar to Tai's the valves have a transition from fully open to fully closed of less than 3ms and have various acoustic standards to ensure quiet operation, while fulfilling energy requirements (Figure 18). Through the study, it was found that the system could be controlled to the established standards, although it was agreed that more research and development needed to take place.

Conclusion

Variable valve timing technology has grown as technological availability increases. The need for ever more efficient, clean, powerful engines has pushed the bar higher within production automotive engines. The trend toward computer controls is

rapidly approaching a limit within the cam engine world and the jump into camless designs is something of the future that holds much promise. Within only a few years, many of the problems have been solved within this exciting new field and within a few more years there is really no idea where development could be. Much like VVT in the cam engine, it will take more research and time to move the electromagnetic system over into production. The problem of transition time has been virtually solved and the seating speed will soon be under control. The main issue to be sorted out is the physical constraints of the systems. With weight and power still being issues, the advancement of materials and electronics will determine the outcome of electromagnetic valves. Despite the problems, the camless engine is the future. The level of control (lift, duration, phase) is practically unheard of in mechanical systems.

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Appendix A

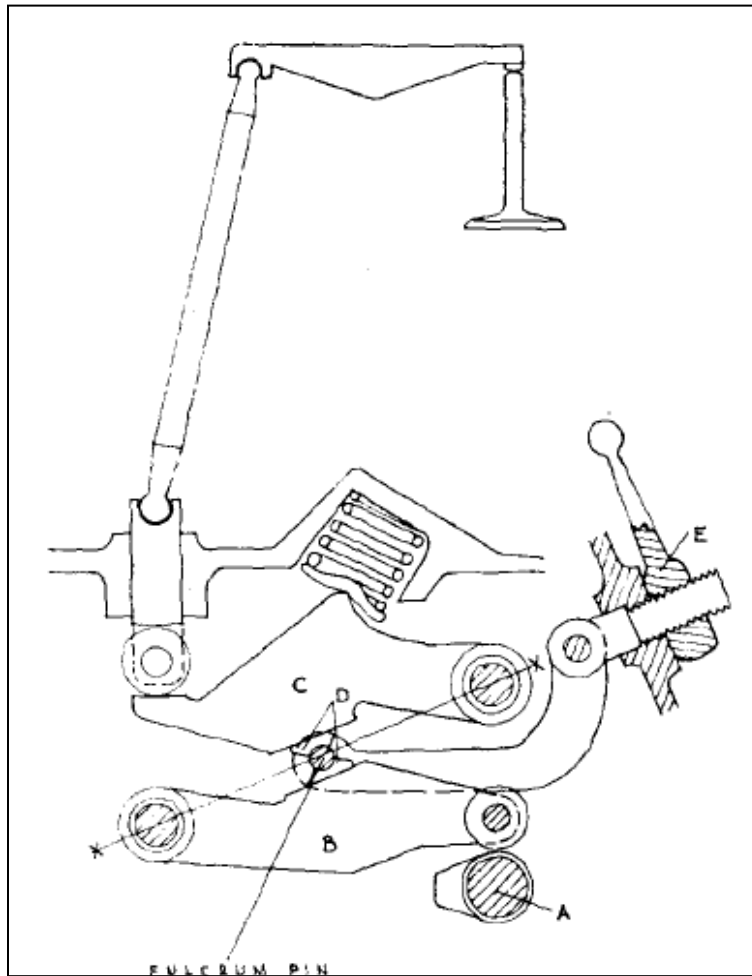


Figure 1: Mechanical device for control of valve lift in aircraft test engine. Screw E is twisted to adjust the arm between C and B so that when A lifts B, C will be advanced or delayed (Aircraft Engineering, 1933)

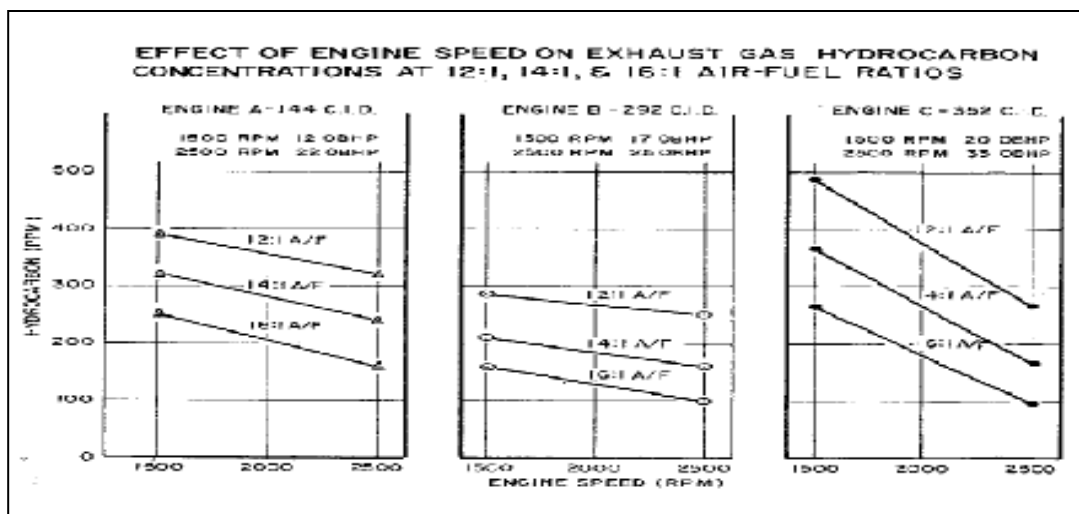


Figure 2: Hydrocarbon concentrations (ppm) based on various A/F ratios (Hagen et al., 1962)

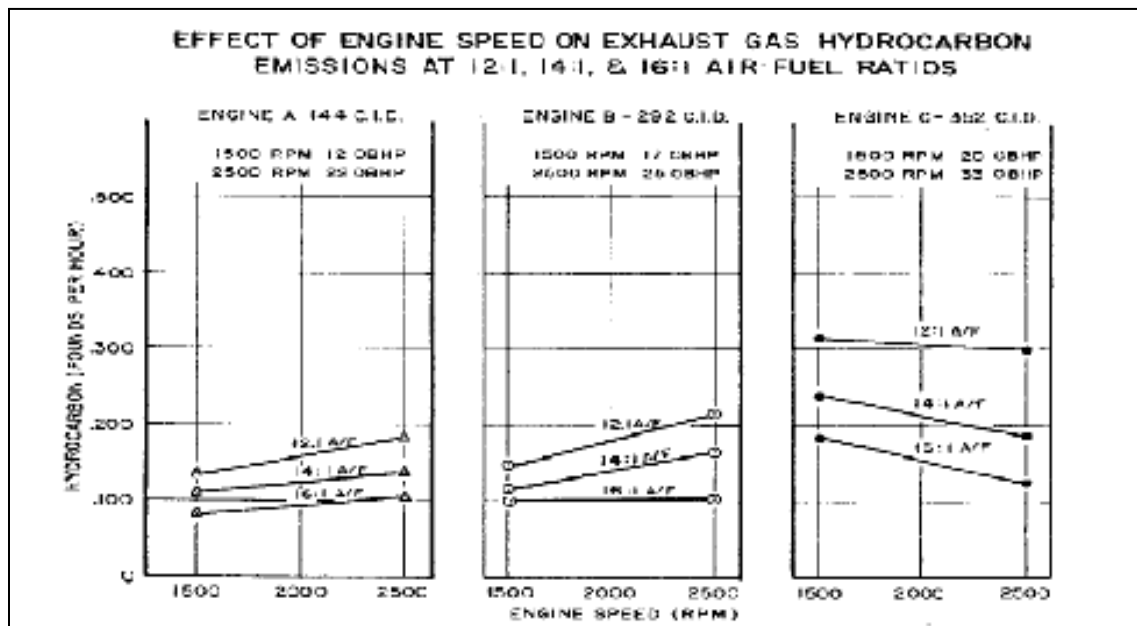


Figure 3: Hydrocarbon emission (lbs/hr) based on A/F ratios and rpm (Hagen et al., 1962)

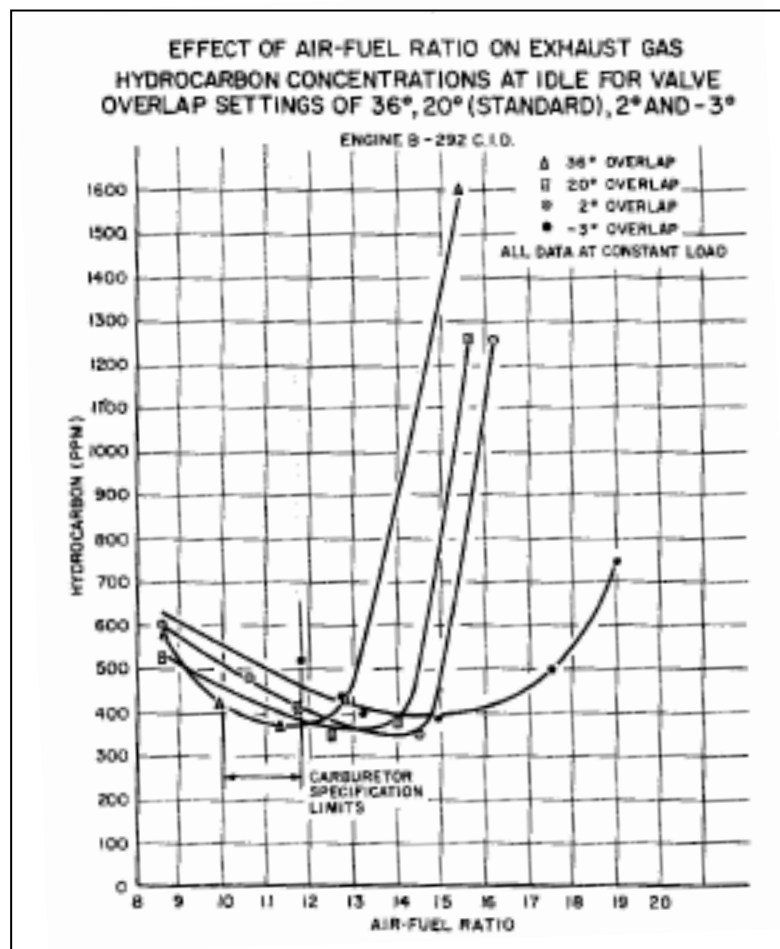


Figure 4: Hydrocarbon concentrations (ppm) based on valve overlap setting and A/F ratio (Hagen et al., 1962)

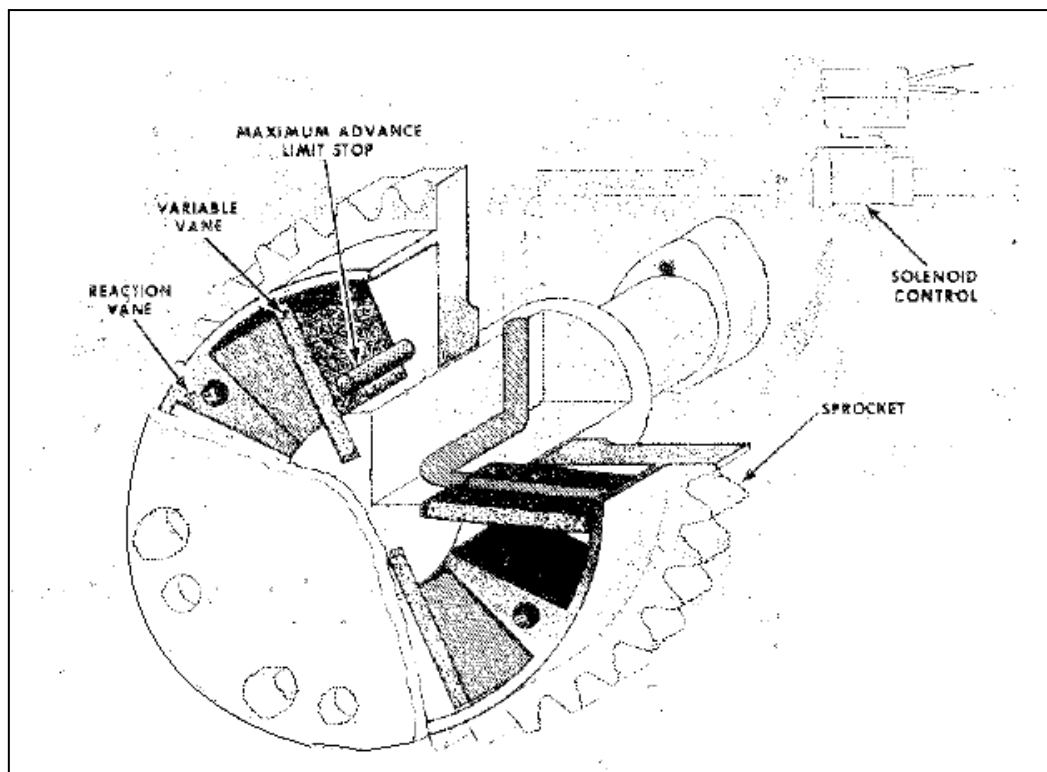


Figure 5: Device for adjusting cam using oil flow regulated by solenoid (Freeman et al. 1972)

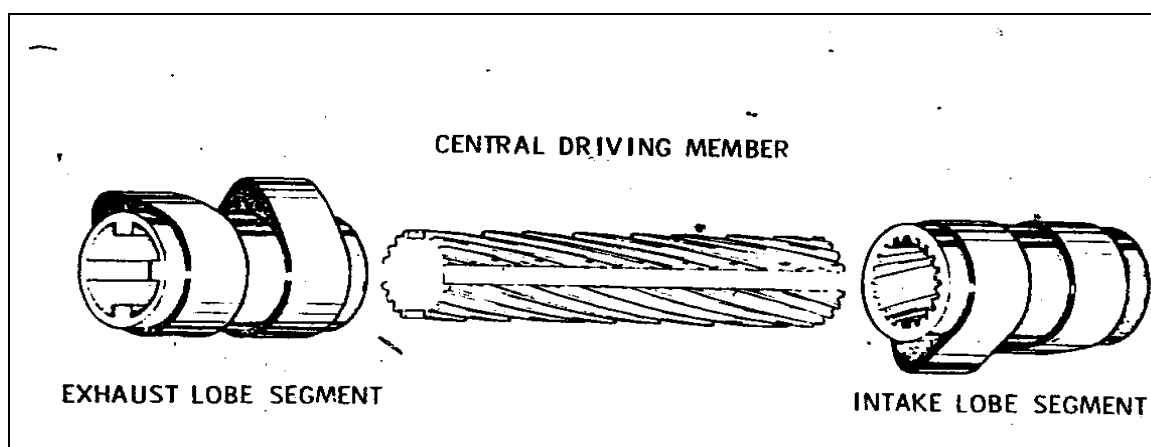


Figure 6: Configuration of camshaft for varying the intake timing without affecting the exhaust timing. Notice the interiors of both segments (Schiele et al., 1974)

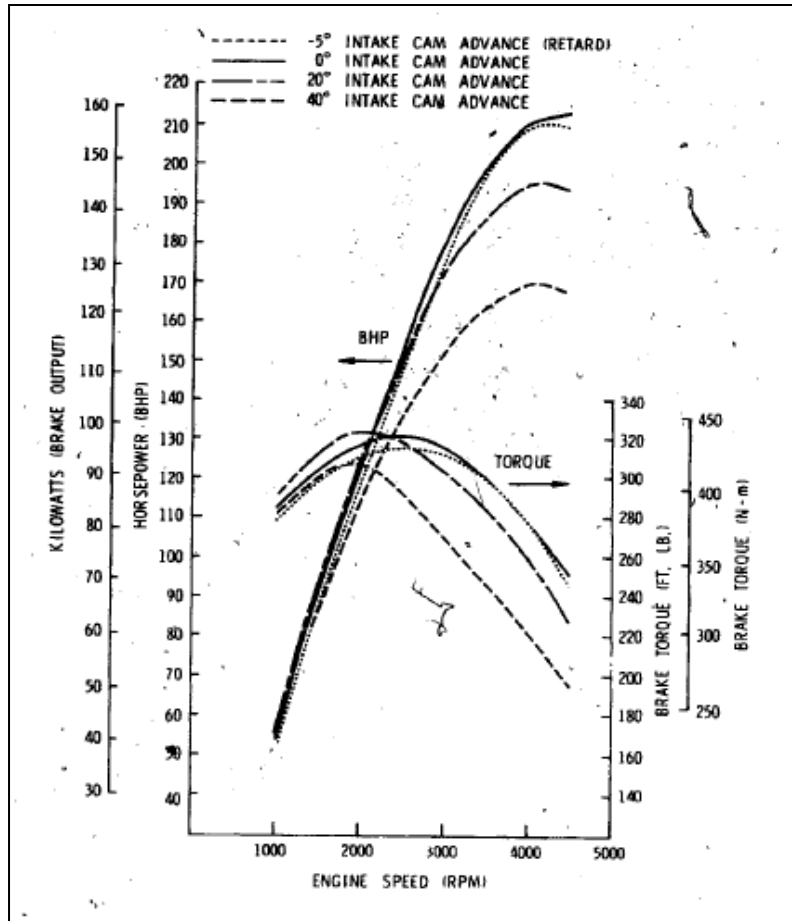


Figure 7: Engine output vs rpm based on several intake cam setups (Schiele et al., 1974)

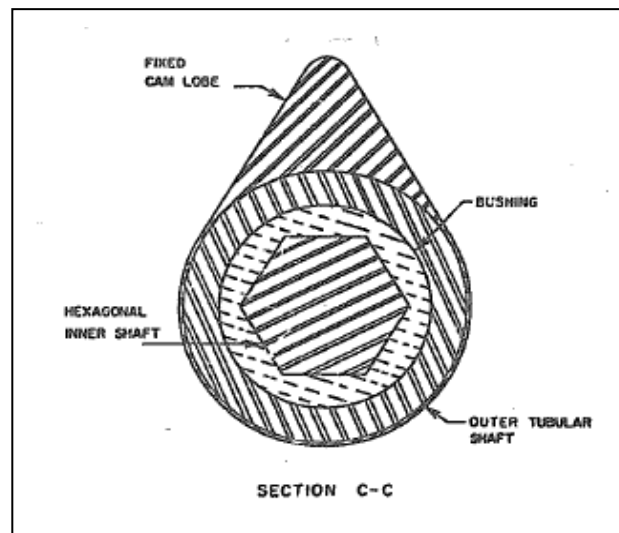


Figure 8: A fixed cam on a rotating shaft (Elrod et al., 1986)

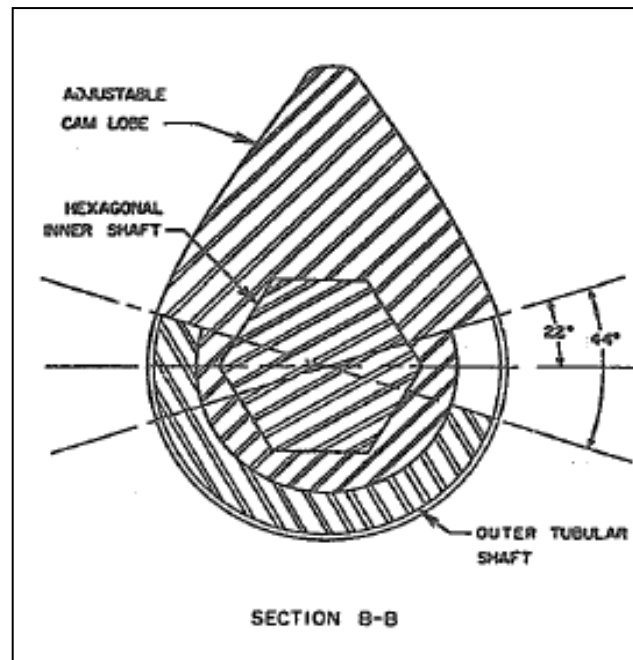


Figure 9: An adjustable cam on a rotating hexagonal shaft used for intake valve timing (Elrod et al., 1986)

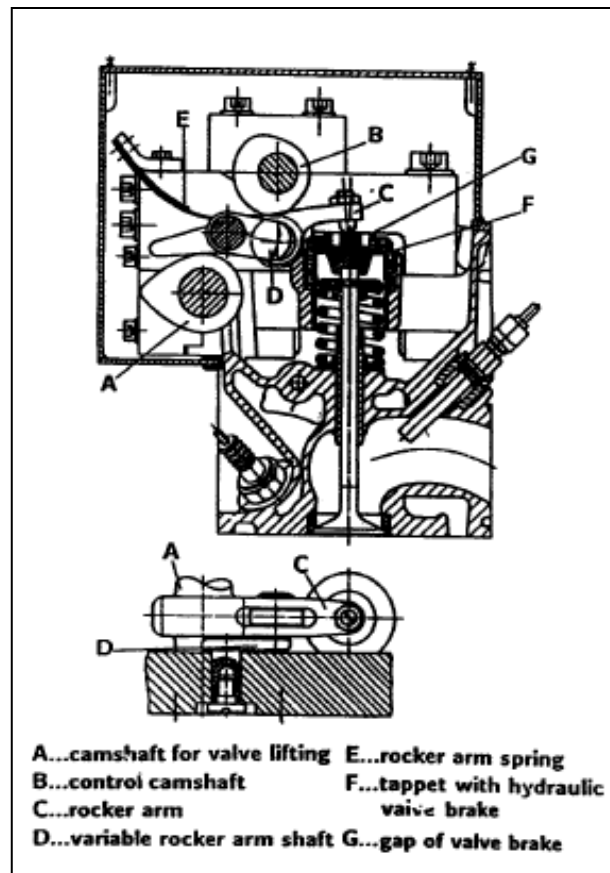


Figure 10: A hydraulic mechanical valve actuation device (Lenz et al., 1988)

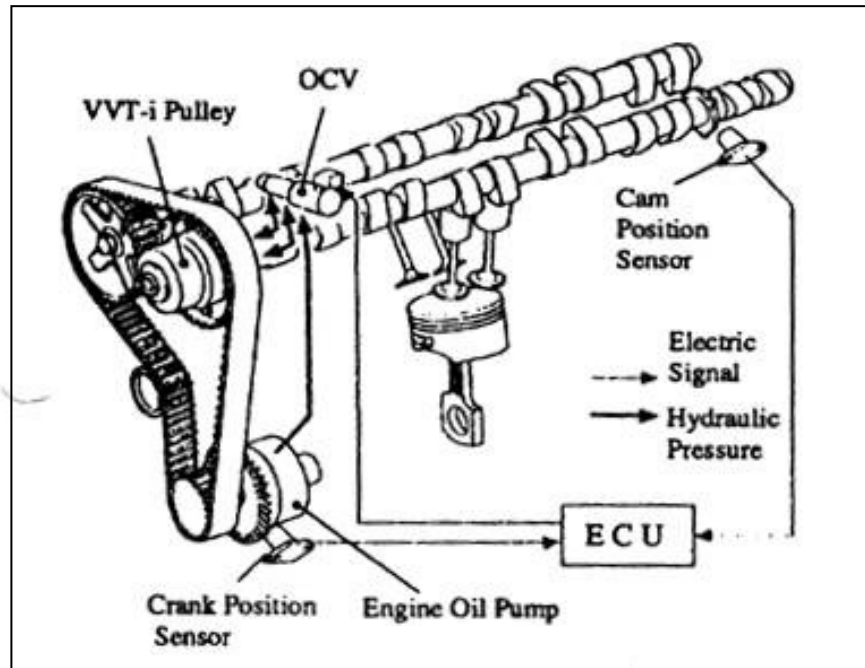


Figure 11: Toyota's pulley driven variable valve timing actuator coupled with an electronic control unit (Moriva et al., 1996)

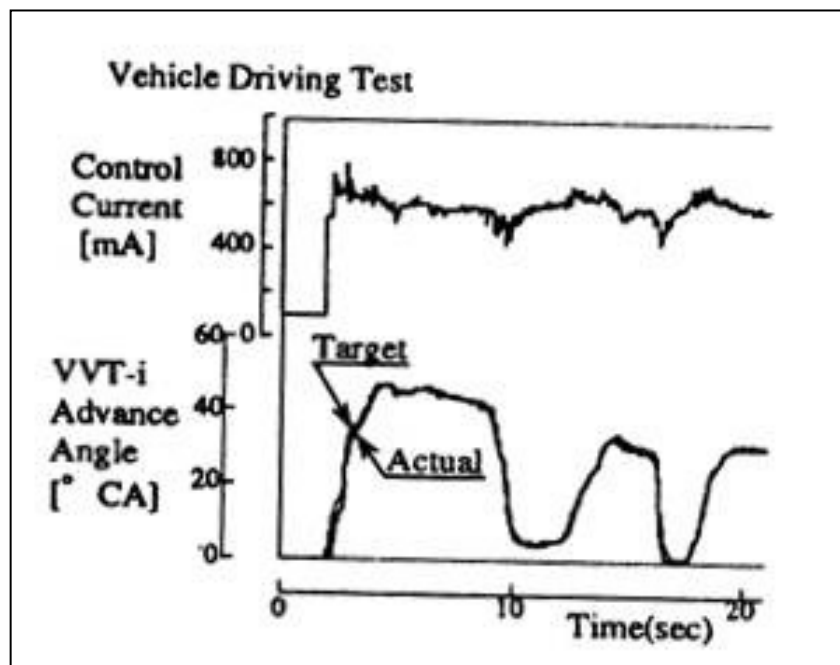


Figure 12: Feedback control for matching advance angle setup in Toyota's vvt device (Moriya et al., 1996)

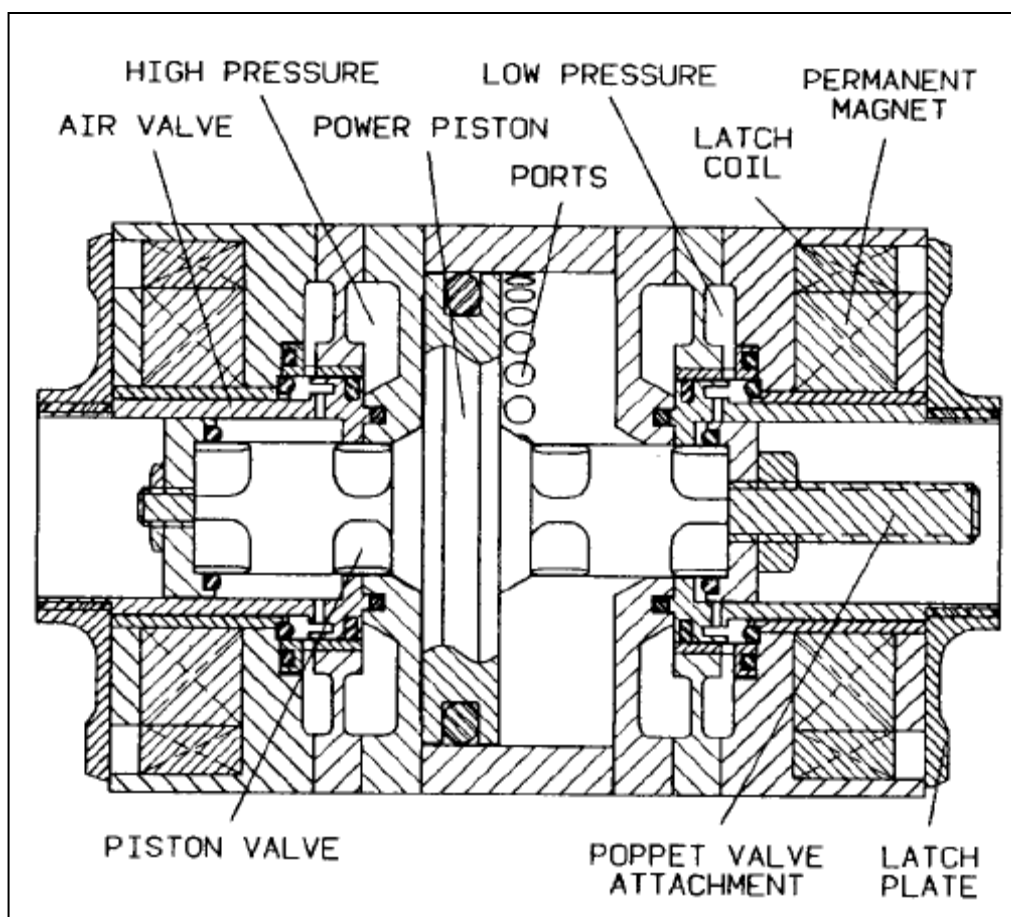


Figure 13: Electro-pneumatic valve timing device (Gould et al., 1991)

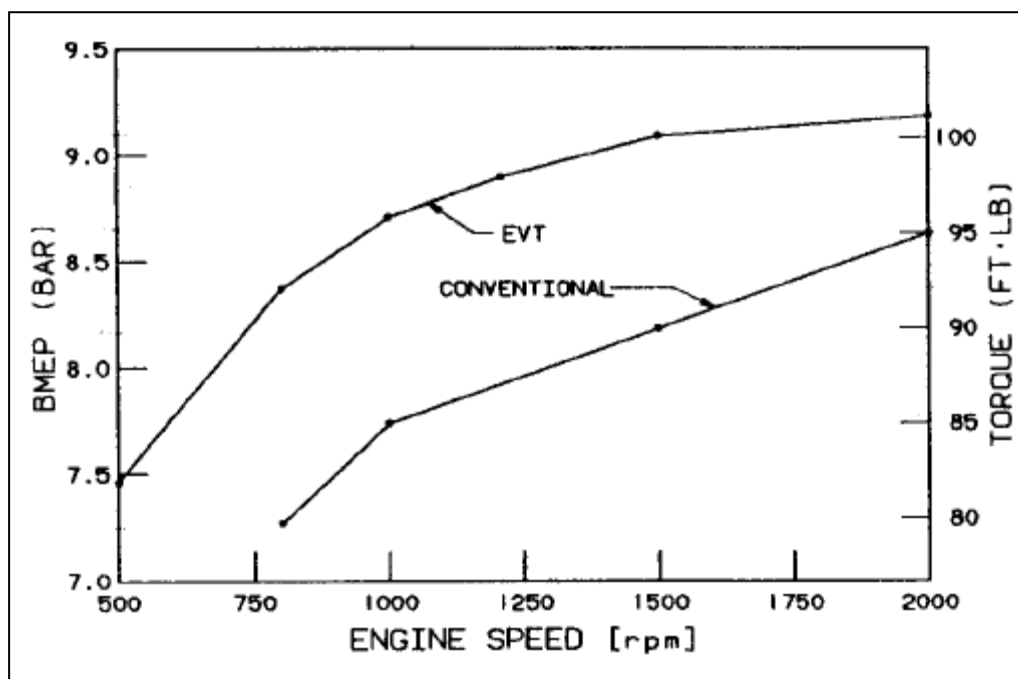


Figure 14: Comparison of electro-pneumatic vvt device with typical engine output (Gould et al., 1991)

ENGINE VALVE CONFIGURATION	VALVE TIMING [CRANK ANGLE DEG.]				EMISSIONS DATA [g/kW-h]			
	IVO	IVC	EVO	EVC	bsfc	bsNOx	bsHC	bsCO
CONVENTIONAL	18°BTC	40°ABC	70°BBC	20°ATC	341.3	14.60	4.02	0.20
EVT, THROTTLED, MIN bsfc	5°BTC	5°ABC	15°BBC	5°BTC	338.1	7.58	4.48	0.20
EVT, UNTHROTTLED, EARLY IVC	5°BTC	75°ATC	15°BBC	5°BTC	326.5	5.95	4.53	0.24
EVT, UNTHROTTLED, LATE IVC	5°BTC	115°ABC	15°BBC	5°BTC	326.3	5.41	4.82	0.35
EVT, THROTTLED, MIN bsNOx	10°BTC	5°ABC	15°BBC	10°ATC	340.1	1.46	5.58	0.24
CONVENTIONAL, 14% EGR, MIN bsNOx	18°BTC	40°ABC	70°BBC	20°ATC	357.2	1.75	6.08	0.21

Figure 15: Performance and emissions data for various timing configurations in an electro-pneumatic vvt device (Gould et al., 1991)

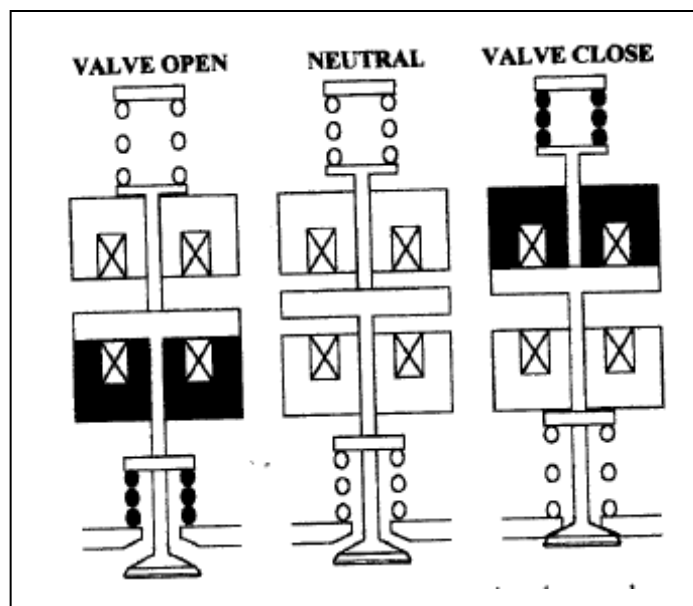


Figure 16: Electromagnetic camless valve actuator in various stages of valve actuation. Black represents the energizing of magnet and compression of spring (Park et al., 2003)

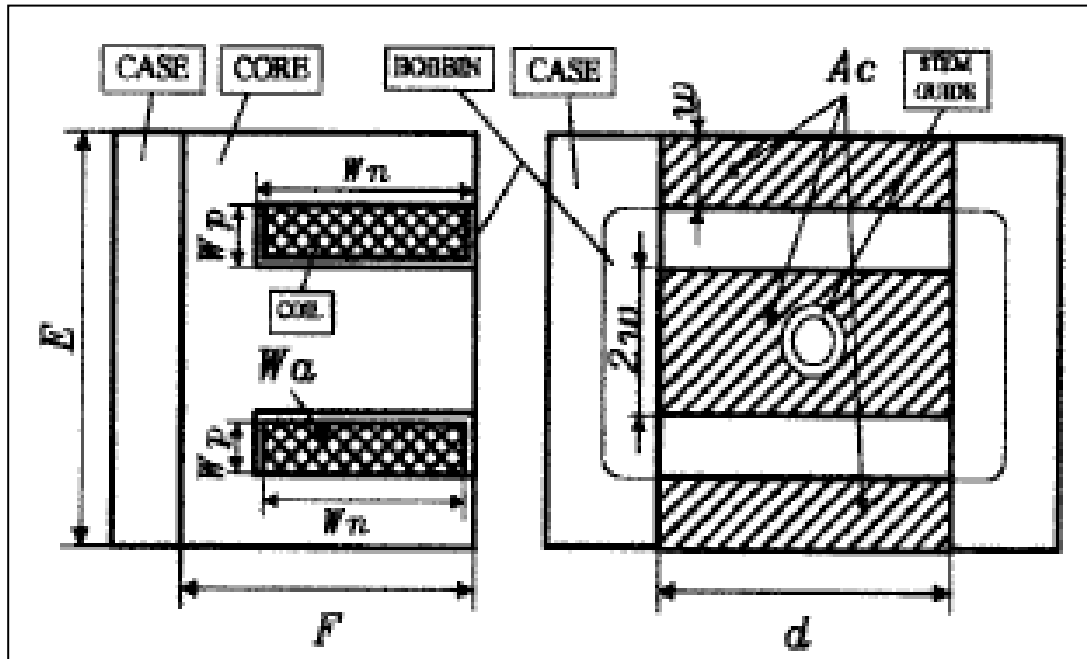


Figure 17: E-shaped electromagnet used in fig 16. Looking down valve stem on the right (Park et al., 2003)

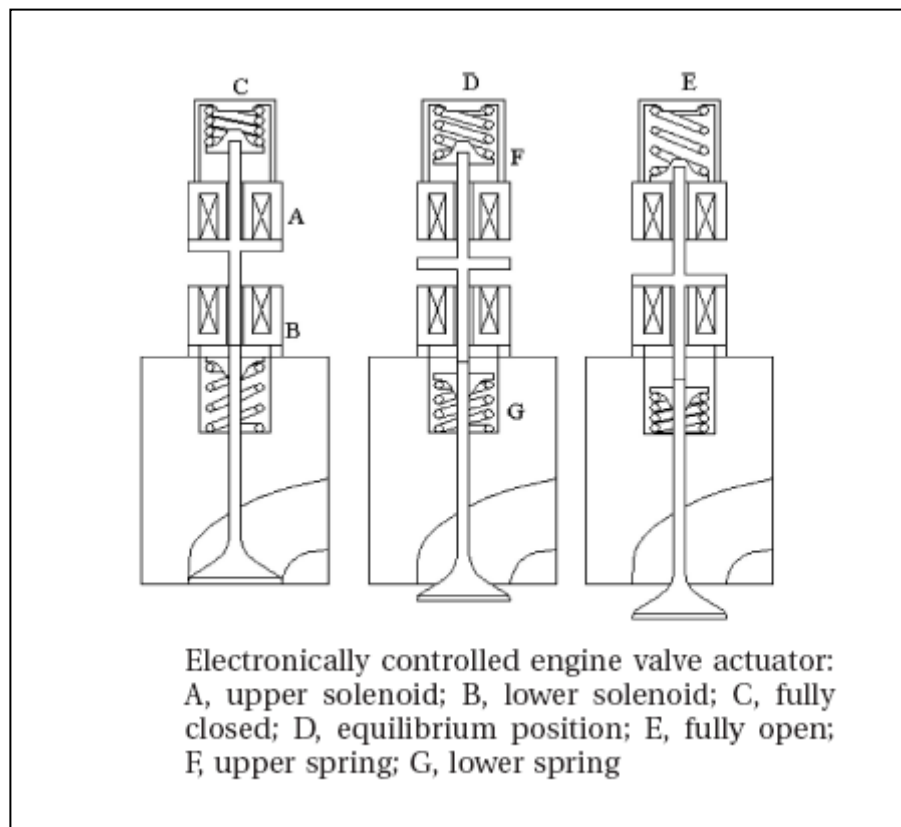


Figure 18: Camless electromagnetically controlled valve actuator in three stages (Stewart et al., 2007)

Appendix B



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Variations on valve timing.

•Production-car engines have progressed remarkably in the past decade. Port-fuel-injection systems have replaced carburetors. Four-valve-per-cylinder technology has made the jump from racing cars to everything from luxury sedans to econoboxes. Now we're seeing a third major trend emerge—variable valve timing. More engines are adopting this technology for a simple reason: to provide a wider range of power. Because an engine's power is primarily limited by the amount of air it can pump in and out of its cylinders, the benefits of variable valve timing (VVT) are best understood by taking a look at the four-stroke piston engine's intake stroke.

In theory, an engine's intake process would be simple. The intake valve would open with the piston at the top of the intake stroke. Then the piston would slowly descend to the bottom of its stroke, so that the intake charge (air and vaporized fuel) would have plenty of time to flow from the intake manifold and thoroughly fill every cubic centimeter within the cylinder. Then the intake valve would snap shut, trapping the full cylinder charge.

That's the theory. In real life, even at a moderate 3000 rpm, the piston performs the intake stroke in an eyeblink—one

one-hundredth (0.010) of a second. Because no valvetrain can pop open a valve instantaneously, the intake valve must begin its gradual opening before the piston begins its violent descent.

Even so, the intake flow can't keep up. For while the piston is yanked downward by a solid mechanical connection to the rotating crankshaft, the intake charge is motivated by more elastic persuasions—pressure differentials.

Just as you inhale to create low pressure in a straw sitting in a glass of soda, the descending piston creates a low-pressure area in the cylinder. And just as atmospheric pressure pressing on the soda in your glass forces it up the straw, atmospheric pressure in the intake manifold (at full throttle) pushes the charge to the lower-pressure region created in the cylinder.

And just as liquid flows slowly through the narrow straw from the big glass, the incoming intake charge is restricted by the narrow intake port, which is much smaller in diameter than the cylinder and blocked partly by an open valve. Even with two intake valves, the cross section of the intake ports is typically no more than one-quarter of the piston area.

This means that the intake charge inevitably lags behind the descending piston. At the bottom of the intake stroke, when the piston is about to start upward again, a column of air and fuel—as much as twenty inches long in some intake systems—is still pouring into the cylinder as quickly as 50 mph.

Ideally, the intake valve would remain open as long as this flow continues, closing exactly when it stops, trapping the maximum amount of air and fuel in the cylinder. At 3000 rpm, that ideal instant might be about 0.002 second after the piston has passed the bottom of its stroke. In crankshaft rotational terms, that would be 36 degrees ABC (after bottom center).

This activity changes considerably at 6000 rpm. The speed and momentum of the intake flow is double what it was at 3000 rpm, and it lags even further behind the piston. The ideal valve closing might now be 0.004 second after bottom center, and at the higher rpm that translates into 144 degrees ABC. In reality, interference with the compression stroke dictates an earlier valve closing, but you get the picture.

What happens at the start of this intake stroke also deserves a look, because it affects valve overlap—that short period when the intake valve is just starting to open and the exhaust valve is almost closed. Although it can be beneficial, a lengthy valve-overlap period is not critical

to developing high power. However, it does have a very important effect on idle quality and smoothness.

During overlap, the pressure in the cylinder, and in the exhaust system, is a bit above atmospheric due to exhaust back pressure. The pressure in the intake system is well below atmospheric because the throttle is closed. Flow always works from high to low pressure, so instead of the intake charge flowing into the cylinder, exhaust gas flows from the cylinder part-way into the intake system. When the exhaust valve finally closes and the intake stroke begins, this same exhaust gas is sucked back into the cylinder before any fresh intake charge begins to flow. This dilution of the charge doesn't help combustion stability, because the spark plug can't ignite exhaust gas very successfully. It's the primary reason why engines with high-rpm-oriented camshafts don't idle smoothly.

Variable-valve-timing (VVT) systems are designed to alter the intake-valve timing to match the engine's constantly varying requirements. Most use a relatively simple mechanism that switches the phasing of the intake camshaft between two positions about twenty degrees apart.

At idle, the VVT system retards the intake camshaft. The intake valves open and close as late as possible, because the late opening minimizes overlap and fosters stable combustion. The late closing isn't desirable, but it's irrelevant at idle.

Just above idle, however, the engine needs to make power, so the VVT mechanism moves the camshaft to the advanced (earlier opening and closing) position. By doing so, cylinder filling is enhanced, because the intake valve's closing is optimized for midrange rpm.

At high rpm, the VVT retards the cam again to better match high-rpm conditions. Although this retarded position reduces valve overlap, the later closing of the intake valve is far more important to efficient cylinder filling because it traps more of the inrushing charge at the end of the intake stroke.

Although the dynamics of the exhaust stroke are different, VVT would reap dividends there as well. But because an intake VVT system alone seems to be worth a power increase of about ten percent, most manufacturers are stopping there for now.

It's only a matter of time, however, before someone perfects a mechanism that will allow each valve to open and close independently. That should be worth further major gains in power as well as fuel efficiency. And it should take the four-stroke piston engine nicely into the next century.

